1.0 INTRODUCTION

The purpose of this EDP is to standardize regulator settings for Massachusetts Electric Company's (MECo) distribution feeders. It was prepared in response to a request by the Massachusetts Department of Public Utilities (now the Massachusetts Department of Telecommunications and Energy) to ensure that we continue to maintain voltage levels as outlined in our report to the MDPU dated September 24, 1991.

While written specifically for Massachusetts Electric, these methods can be used for determining regulator settings on distribution feeders for both Granite State Electric Company and The Narragansett Electric Company. However, each state has different voltage standards that must be adhered to, so engineers should verify that the maximum and minimum voltage levels obtained using these methods do not exceed individual state regulations.

2.0 MASSACHUSETTS ELECTRIC COMPANY'S CONSERVATION VOLTAGE REDUCTION PHILOSOPHY

Conservation Voltage Reduction (CVR) refers to the generic practice of saving energy by providing electric service to customers at the lowest practical voltage level while still meeting ANSI Standard C84.1 "American National Standard for Electric Power Systems and Equipment – Voltage Ratings (60 Hz)".

Customer voltages are maintained in the range of ± 5% of a nominal voltage (120 volts for example) at the customer's service entrance, as defined by Range A of the above Standard. This equates to Range A service voltages of from 114 volts to 126 volts during normal operating conditions.

Abnormal operating conditions must also be considered. Under NEPOOL Operating Procedure No. 4, 5% voltage reduction conditions can be implemented. ANSI C84.1 Range B allows for temporary voltages above and below Range A limits, provided corrective measures are undertaken within a reasonable time to improve voltages to meet Range A requirements. Service voltages need to be able to remain within Range B guidelines during these abnormal operating conditions. Range B voltages are allowed to range from 8.3% below nominal (110 volts) to 5.8% above nominal (127 volts).

ANSI Ranges A and B define the voltage range limitations for the Conservation Voltage Reduction program. The CVR range must be within Range A under normal operating conditions and have the ability to withstand a further 5% voltage reduction during abnormal operating conditions (NEPOOL OP #4) and still remain within Range B limits.

The objective of the CVR program is to save energy by keeping feeder voltages as low as practical while meeting the limits described above. Of greatest concern, then, will be the last customer's voltage. The last customer's service voltage should be no greater than 116 volts (0.967 per unit or pu) on peak and within 1% of the on peak value during off peak conditions. This assures that the average feeder voltage is as low as practical at all times. Using an assumption of 4 volts (0.033 pu) secondary drop, last customer primary voltages should be fixed at 1.0 pu.

3.0 METHODOLOGY

The method used in the following text uses the equation governing the regulator's response to a given condition to derive the regulator settings (equation 1). There are three variables in the equation: R, X and V_{float}. The method firsts assigns a float voltage of 120 volts (1.0 pu) and solves for the remaining two variables using the regulator response equation for both peak and light load conditions. Equations (2) and (3) are the direct equations for determining R and X using this method.

Some may find it more convenient to solve the two simultaneous equations themselves rather than using the "simplified" equations (2) and (3). Whichever method is used, it should be remembered that two static conditions are being used to determine settings to govern a dynamic operation. This may sometimes result in values of R, X and V_{float} that experience tells you should not be used (i.e. extremely high or negative values for R and X). This may happen when there is a large difference between the peak and light load voltage drops or when the light load power factor is more lagging than the peak load power factor. Some judgment must be used as to the appropriateness of the peak and light load assumptions, as well as the end result.

Two examples showing some of the concerns and options are given at the end of this document.

4.0 DETERMINING VOLTAGE REGULATOR SETTINGS

Regulator settings of R, X and V_{float} need to be chosen to achieve last customer voltages as indicated in Section 2.0.

a) Using load and power factor data for peak and light load conditions, determine voltage drop from the station regulator to the last customer.

b) Determine necessary regulator output voltage for peak and light load conditions to maintain the desired last customer voltage.

4.0 DETERMINING VOLTAGE REGULATOR SETTINGS (continued)

c) Equation (1) is the basic equation governing regulator output voltage.

$$V_{out}\text{ (p.u.)} = \left[\frac{I\,(R\cos 2 + X\sin 2)}{CT} + V_{float}\right]\frac{VT\sqrt{3}}{V_{L\text{-}L}} \qquad (1)$$

Where:

V_{out}	=	Regulator output voltage (per unit)
I	=	Load current (amperes)
R	=	R setting of regulator (volts)
X	=	X setting of regulator (volts)
V_{float}	=	Float voltage setting of regulator (volts)
CT	=	CT high side amperes
VT	=	VT ratio of regulator
2	=	Power factor angle
$V_{L\text{-}L}$	=	Nominal line to line voltage (volts)

The actual R and X settings can then be determined using equations (2) and (3) (which were derived from equation 1) for both peak and light load conditions.

Equations (2) and (3) are for V_{float} = 1.0 p.u.

$$V_{float} = \frac{V_{L\text{-}L}}{VT\sqrt{3}} = 1.0\text{ p.u.}$$

$$X = \frac{V_{L\text{-}L}\,(CT)}{\sqrt{3}\,(VT)\,(\tan 2_p - \tan 2_l)}\left[\frac{V_{out\text{-}p} - 1}{I_p\cos 2_p} - \frac{V_{out\text{-}l} - 1}{I_l\cos 2_l}\right] \qquad (2)$$

$$R = \left[\frac{V_{L\text{-}L}\,(CT)\,(V_{out\text{-}p} - 1)}{\sqrt{3}\,(VT)\,I_p\cos 2_p}\right] - X\tan 2_p \qquad (3)$$

Where:

$V_{out\text{-}p}$	=	Output voltage of regulator – for peak load (per unit)
$V_{out\text{-}l}$	=	Output voltage of regulator – for light load (per unit)
Ip	=	Peak load current (amperes)
I_l	=	Light load current (amperes)
2_p	=	Power factor angle for peak load
2_l	=	Power factor angle for light load

4.0 DETERMINING VOLTAGE REGULATOR SETTINGS (continued)

d) Using equation (4), check for change in regulator output voltage for the largest switched capacitor bank.

$$\text{Change in voltage (volts)} = \frac{\text{(cap amps) (X)}}{\text{CT}} \qquad (4)$$

If the change in regulator output voltage is greater than 3% (3.6 volts on a 120 volt basis), X can be limited to achieve a more acceptable value. X can be determined from equation (5), again using the amperes of the largest switched capacitor bank.

$$X = \frac{(3.6)\ (\text{CT})}{(\text{cap amps})} \qquad (5)$$

Adjusted values for R and V_{float} must then be determined. Solve for R and V_{float} using equations (6) and (7).

$$R = \frac{\frac{(\text{CT})\ V_{L\text{-}L}}{\text{VT}\sqrt{3}} (V_{out\text{-}p} - V_{out\text{-}l}) - X(I_p \sin 2_p - I_l \sin 2_l)}{I_p \cos 2_p - I_l \cos 2_l} \qquad (6)$$

$$V_{float} = \frac{(V_{out\text{-}p})\ (V_{L\text{-}L})}{\text{VT}\sqrt{3}} - \frac{I_p\,(R \cos 2_p + X \sin 2_p)}{\text{CT}} \qquad (7)$$

e) Bandwidth:

Set at ±0.75 volts for modern installations (older regulators may have bandwidth set at a minimum of twice the step size if desired).

Time Delay:

Set at 60 seconds (increased time delay, not bandwidth, should be used to limit the number of operations on a regulator if necessary).

First House Protection:

$$\text{Upper Limit} = 127 + \frac{A\ (120)}{100}\ \text{volts}$$

Where A = the percent drop from the station to the first customer with the load equal to the emergency rating of the feeder.

5.0 SAMPLE CALCULATIONS

<u>Example 1: Straightforward example using Equations (2) and (3).</u>

13,200 volt feeder		
Peak Load:	290 amps at 0.99 lagging	5.5% primary voltage drop
Light Load	95 amps at unity	1.7% primary voltage drop
CT high side:	400amps	
VT ratio:	66.7	
Largest Cap Bank:	1200 kvar	

$$\text{Set } V_{float} = 1.0\text{pu} = \frac{13200}{(66.7)\sqrt{3}} = 114 \text{ V.}$$

From Equation (2):

$$X = \frac{V_{L\text{-}L}\,(CT)}{\sqrt{3}\,(VT)\,(\tan 2_p - \tan 2_l)} \left[\frac{V_{out\text{-}p} - 1}{I_p \cos 2_p} - \frac{V_{out\text{-}l} - 1}{I_l \cos 2_l}\right]$$

$$X = \frac{13200\,(400)}{\sqrt{3}\,(66.7)\,(\tan 8.1^o - \tan 0^o)} \left[\frac{1.055 - 1.0}{290\,(0.99)} - \frac{1.017 - 1.0}{95\,(1.0)}\right] = 4.05$$

Set X = 4

From Equation (3):

$$R = \left[\frac{V_{L\text{-}L}\,(CT)\,(V_{out\text{-}p} - 1)}{\sqrt{3}\,(VT)\,I_p \cos 2_p}\right] - X \tan 2_p$$

$$R = \left[\frac{13200\,(400)\,(1.055 - 1)}{\sqrt{3}\,(66.7)\,(290)\,(0.99)}\right] - 4 \tan 8.1^o = 8.18$$

Set R = 8

Checks:

- Check change in regulator output voltage when largest switched capacitor bank comes on. Full load amperes for a 1200 kvar bank at 13.2kV= 52.5 amps

  From Equation (4): change in voltage (volts) $= \frac{(52.5)\,(4)}{400} = 0.52$ volts < 3.6 volts O.K.

- Can also check results using Regulator Response Equation where:
  R = 8 X = 4 $V_{float} = 114$

5.0 SAMPLE CALCULATIONS (continued)

Example 1 (continued)

From Equation (1) at peak load:

$$V_{out}\ (\text{p.u.}) = \left[\frac{I\ (R\cos 2 + X\sin 2)}{CT} + V_{float}\right]\frac{VT\sqrt{3}}{V_{L\text{-}L}}$$

$$\text{Peak Load } V_{out}\ (\text{p.u.}) = \left[\frac{290\ (8\ (0.99) + 4\ (0.14))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$= \frac{(120.15)\ (66.7)\sqrt{3}}{13200} = 1.052\ \text{p.u.}$$

$$\text{Light Load } V_{out}\ (\text{p.u.}) = \left[\frac{90\ (8\ (1) + 4\ (0))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$= \frac{(115.8)\ (66.7)\sqrt{3}}{13200} = 1.013\ \text{p.u.}$$

So….	Peak Load	Light Load	
Regulator Output Voltage	1.052p.u.	1.013p.u.	
Primary Voltage Drop	-.055	-.017	
Last Customer Primary Voltage	0.997p.u.	0.996p.u.	→ O.K.

By rounding both the values of R and X down to the nearest integer, the regulator output voltages are slightly less than the 1.055 p.u. at peak load and 1.017 at light load. R and X values can be adjusted if necessary. The important point here is that the last customer primary voltages for both peak load and light load be approximately 1.0 p.u. to meet the guidelines of CVR for the MDTE.

5.0 SAMPLE CALCULATIONS (continued)

Example 2: Solving Simultaneous Equations Using Equation (1) for Two Cases.
(Example includes option of setting X value first.)

13200 volt feeder
Peak Load: 290 amps at 0.99 leading 5.5% primary voltage drop
Light Load: 95 amps at 0.99 lagging 1.7% primary voltage drop
CT high side: 400 amps
VT ratio: 66.7
Largest Cap Bank: 1200 kvar

$$\text{Set } V_{float} = 1.0\text{pu} = \frac{13200}{(66.7)\sqrt{3}} = 114 \text{ V.}$$

A. Setting R value first

From Equation (1) at peak load (assuming the 5.5% primary voltage drop):

$$V_{out}\,(\text{p.u.}) = \left[\frac{I\,(\,R\cos 2 + X\sin 2\,)}{CT} + V_{float}\right]\frac{VT\sqrt{3}}{V_{L\text{-}L}}$$

$$1.\,055 = \left[\frac{290\,((R)\,(0.99) - (X)\,(0.14))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$0.055 = 0.0628\,R - 0.00089\,X$$

$$\text{(a)} \qquad X = 7.06\,R - 61.80$$

From Equation (1) at light load (assuming the 1.7% primary voltage drop):

$$V_{out}\,(\text{p.u.}) = 1.017 = \left[\frac{95\,((R)\,(0.99) + (7)\,(0.14))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$\text{(b)} \qquad 0.017 = 0.0021\,R + 0.00029\,X$$

Substituting Equation (a) for X in Equation (b):

$$0.017 = 0.0226\,R - 0.0179$$
$$0.0349 = 0.0226\,R$$
$$R = 1.5 \qquad \textbf{Set R = 2}$$

From Equation (a):

$$X = 7.06\,(2) - 61.80$$
$$X = -47.7 \qquad \textbf{No Good}$$

You will always get a negative X value when the light load condition is more lagging than the peak load condition. When this occurs, set the X value first, (rather than V_{float} as in first part of example.)

5.0 SAMPLE CALCULATIONS (continued)

Example 2 (continued)

B. Setting X value first

Largest switched capacitor bank 1200 kvar = 52.5 amps at 13.2kV

Rather than going to maximum change in regulator output when the capacitor switches (3.6 volts) as in Equation (5), try limiting change to 1 volt.

From Equation (5):

$$X = \frac{(1\text{ volt})\,(400\text{ amps})}{(52.5\text{ amps})} = 7.6\text{ volts}$$

Set X = 7

Now Solve for R and V_{float} setting up 2 equations from Equation (1)

From Equation (1) at peak load:

$$1.055 = \left[\frac{290\,(R\,(.99) - 7\,(0.14))}{400} + V_{float}\right]\frac{(66.7)\sqrt{3}}{13200}$$

(c) $1.05498 = 0.00628\,R + 0.00875\,V_{float}$

From Equation (1) at light load:

$$1.017 = \left[\frac{95\,(R\,(0.99) + 7\,(0.14))}{400} + V_{float}\right]\frac{(66.7)\sqrt{3}}{13200}$$

$1.01702 = 0.0021\,R + 0.00875\,V_{float}$

(d) $R = 484.3 - 4.17\,V_{float}$

Substituting Equation (d) for R in Equation (c):

$0.0174\,V_{float} = 1.9864$

$V_{float} = 113.9$

Set V_{float} = 114

From Equation (d):

$R = 484.3 - 4.17\,(114)$

$R = 8.92$

Set R = 9

5.0 SAMPLE CALCULATIONS (continued)

Example 2 (continued)

Check results for R = 9, X = 7, V_{float} = 114

From Equation (1) at peak load:

$$\text{Peak Load } V_{out}\text{ (p.u.)} = \left[\frac{290\,(9\,(0.99) + 7\,(0.14))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$= \frac{(119.7)\,(66.7)\sqrt{3}}{13200} = 1.048 \text{ p.u.}$$

From Equation (1) at light load:

$$\text{Light Load } V_{out}\text{ (p.u.)} = \left[\frac{95\,(9\,(0.99) + 7\,(0.14))}{400} + 114\right]\frac{(66.7)\sqrt{3}}{13200}$$

$$= \frac{(116.3)\,(66.7)\sqrt{3}}{13200} = 1.018 \text{ p.u.}$$

So….

	Peak Load	Light Load
Regulator Output Voltage	1.048p.u.	1.018p.u.
Primary Voltage Drop	-.055	-.017
Last Customer Primary Voltage	0.993p.u.	1.001p.u. → O.K.